

Versatile assembly of *p*-carboxylatocalix[4]arene-*O*-alkyl ethers

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Crystallisation of lower-rim tetra-*O*-alkylated *p*-carboxylatocalix[4]arenes from pyridine results in the formation of both bi-layer and pillar type supramolecular motifs. Full alkylation at the calixarene 5 lower rim has significant influence over the supramolecular self-assembly motif, including preclusion of pyridine guest molecules from the calixarene cavity in the solid state.

Introduction

The controlled assembly of molecular components into large structures is a challenging goal in supramolecular chemistry. Calix[4]arenes are (typically) bowl-shaped molecules that are useful for 10 this purpose due to the ease with which synthetic modification can a) control their conformation, and b) introduce complementary functional groups in order to facilitate or aid self-assembly.¹ Notable examples of self-assembled calix[4]arene systems include bi-layer arrays,² hexameric/dodecameric molecular capsules,³ and non-covalent nanotubes.^{3b,4} *p*-Sulfonatocalix[4]arene (1, Figure 1A) has been widely investigated in this context, and although the molecule typically packs in up-down anti- 15 parallel bi-layers in the solid state,²ⁱ⁻ⁿ back-to-back packing induces curvature in the resulting supramolecular structures to produce dodecameric molecular capsules (that can be of either icosahedral or cuboctahedral geometry) and nanotubes, the latter of which are all of similar diameter.^{3b,3e}

In comparison to the *p*-sulfonatocalix[n]arenes, their carboxylato analogues - general notation 20 *p*CO₂[n]s - have received little attention as supramolecular building blocks in non-covalent assemblies. In recent studies we began to explore the self-assembly of the *p*-carboxylatocalix[4]arenes and have demonstrated the formation of non-covalent nanotubular assemblies of 2 and 3, and a bi-layer array of 4 - all by crystallisation from pyridine (Py).^{4h,4j} In addition to this, we have also characterised inter-penetrated networks of a new type of nano-capsule in the cesium and rubidium salts 25 of O-Me derivative 5.⁵ The aforementioned assembly of 2 – 4 from pyridine occurs by a common supramolecular motif that is based on dimerisation of each calixarene through complementary CO₂H...Py hydrogen bonding as shown for compound 4 in Figure 1B.

It is well known that careful substitution at the lower rim of the general calix[4]arene skeleton 30 allows one to control the conformation of the resulting molecules.⁶ To illustrate this, compound 2 adopts a cone conformation in the solid state due to favourable hydrogen bonding interactions at the lower rim.^{4h} Compounds 3 and 4 also adopt a cone conformation due to the presence of two hydroxyl groups at the lower rim in each case.^{4j} For compound 5 and other related compounds,^{5,7} tetra-*O*-alkylation to afford the methoxy derivative produces a fluxional molecule, a feature that is attributable 35 to the passage of the small methoxy groups through the calixarene annulus. Tetra-*O*-alkylation to afford O-Prn or O-Bu_n derivatives affords conformationally restricted calixarenes that cannot undergo such fluxional movement. In the solid state these calix[4]arenes typically exist in a type of pinched cone conformation such that two phenyl rings come into the centre of the molecular cleft and two splay open. Formylation by literature procedure affords *p*-formyl derivatives 6 and 7⁸ that can subsequently converted to carboxylic acids 8 and 9 respectively.⁹

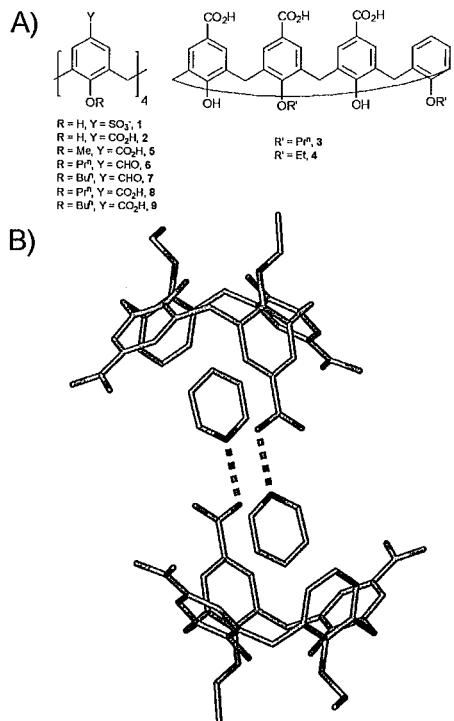


Fig. 1 A) Schematic of calix[4]arenes 1 – 9. B) Dimerisation of 4 by crystallisation from pyridine with a $CO_2H \cdots Py$ hydrogen bonding interaction shown as a dashed line.⁴ Hydrogen atoms omitted for clarity.

As we were able to assemble non-covalent nanotubes from either 2 or 3 via intermolecular interactions as shown in Figure 1B,^{4h,4j} we investigated the effect that full calixarene lower rim alkylation would have on this assembly motif. We anticipated that this degree of lower-rim substitution would cause distortion within the cone conformation of the calixarene in the solid state, and would likely preclude the inclusion of a pyridine guest in the cleft of either 8 or 9.

10 Results and Discussion

p-Formylcalix[4]arene precursors

During the synthesis of 8 and 9, calix[4]arenes 6 and 7 were isolated as precursors. Both were recrystallised from chloroform and were analysed by single crystal X-ray diffraction studies.[‡] In both cases the resulting crystals are weakly diffracting but satisfactory structural solutions were obtained.

Both calixarenes crystallise in the absence of solvent and are seen to adopt the expected (and common) pinched cone conformation (Figure 2).¹⁰ This, as described for some tetra-O-alkylated calix[4]arenes in the introductory section, results in two aryl rings pinching towards the centre of the molecule while the remaining two rings splay to afford the pinched cone conformer in each case.

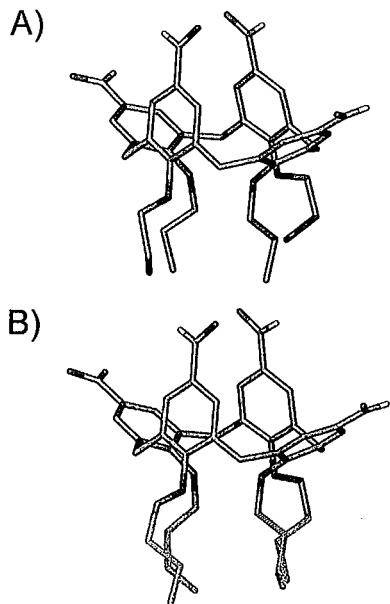


Fig. 2 Single crystal X-ray structures of the p-formyl calix[4]arenes 6 and 7. A) p-Formyl tetrapropoxycalix[4]arene. B) p-Formyl tetrabutoxycalix[4]arene. Hydrogen atoms (except for formyl groups) are omitted for clarity.

5 Tetrapropoxy-p-carboxylatocalix[4]arene·pyridine (8·Py)

Crystallisation of calixarene 8 from pyridine by slow evaporation affords colourless single crystals that are suitable for X-ray diffraction studies.‡ These crystals were found to be weakly diffracting and required synchrotron radiation to afford a satisfactory structural solution. The crystals are in a triclinic cell and structure solution was performed in the space group P-1. The asymmetric unit in 8·Py

10 comprises two molecules of 8 and nine pyridines of crystallisation. Both molecules adopt similar pinched cone conformations akin to that of their formyl precursor (Figure 3A). The lower rim nature of each crystallographically unique molecule of 8 in 8·Py is similar in that one of the alkyl chains points away from the centre of each calixarene base. As in all of our previously encountered pCO₂[4]

pyridine solvates, 4h,4j Py molecules (eight of nine) are located so as to form favourable hydrogen

15 bonding interactions with the upper rim calixarene carboxylic acid groups (shown for one molecule of 8 in Figure 3A). There are a total of eight N···HO interactions and six CH···O interactions with respective distance ranges of 1.794 – 1.861 Å and 2.570 – 2.784 Å. Two of the pyridines are oriented so as to form CH···O interactions with neighbouring molecules of 8 relative to the one with which they form N···HO interactions (two CH···O distances of 2.769 and 2.819 Å). Symmetry expansion of the

20 molecules of 8 shows them to form a pillar, the centre of which is between the lower rim alkyl chains that point away from the calixarene bases (Figure 3B). Space filling representation of the extended structure of 8·Py (Figure 3C) shows the pillars (red) to be nearly isolated and to be separated by layers by Py molecules (blue).

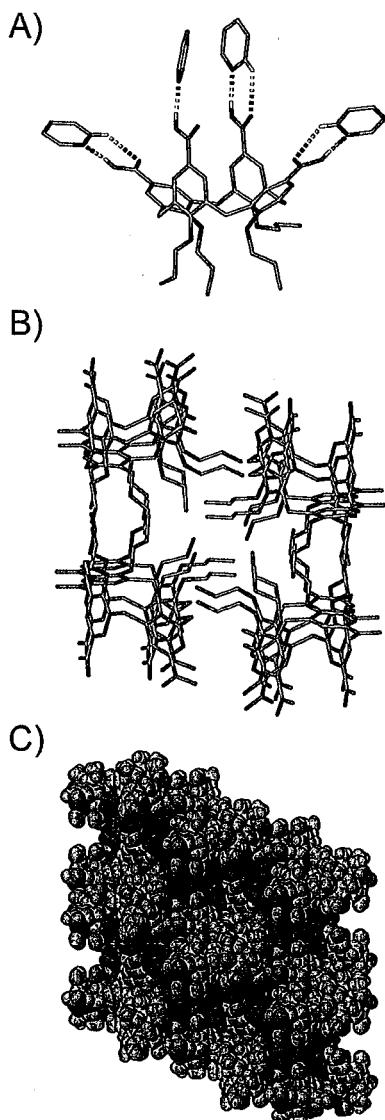
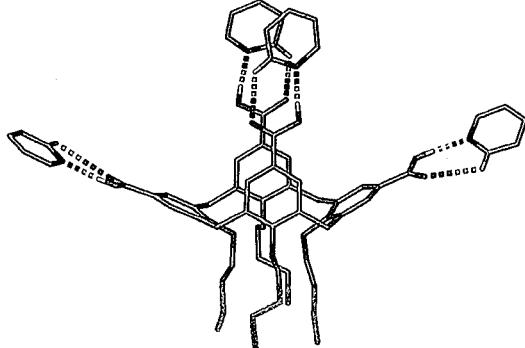


Fig. 3 A) Hydrogen bonding interactions (dashed lines) between four pyridines of crystallisation and one molecule of 8 in the crystal structure of 8-Py. B) Single pillar formed in the extended structure of 8-Py. C) Space filling representation of the extended structure of 8-Py showing pillars (red) and 5 pyridine molecules (blue) – with pillars running out of the plane of the page. Hydrogen atoms omitted for clarity in both A (except those involved in H-bonding) and B.

The ninth pyridine of crystallisation is located between two molecules of 8 and although it does not form interactions with any calixarene carboxylic acid groups, it does form a CH \cdots π interaction with a calixarene aromatic ring (CH \cdots aromatic centroid distance of 2.677 Å). In addition to this, one of the 10 eight Py molecules involved in CO₂H H-bonding also forms a CH \cdots π interaction with the ninth Py (CH \cdots aromatic centroid distance of 2.543 Å). Notably, and in contrast to all of our previously characterised pyridine solvates of pCO₂[n]s, none of the Py molecules are located within the calixarene cavity due to the conformational distortion in the solid state that is imposed via O-alkylation. The direct result of this substitution is that Py omission prevents the typically observed 15 pCO₂[4] dimerisation that is shown in Figure 1B, thereby altering self-assembly relative to the previously reported supramolecular motif.4h,4j

Tetra-butoxy-p-carboxylatocalix[4]arene-pyridine (9-Py)

Crystallisation of 9 from pyridine by slow evaporation affords colourless single crystals that are suitable for X-ray diffraction studies.‡ The crystals are in a triclinic cell and structure solution was performed in the space group P-1. The asymmetric unit comprises one molecule of 9 and five and a half pyridines of crystallisation. As is the case for 6 – 8, calixarene 9 is found to exist in the expected 5 pinched cone conformation in the solid state (Figure 4). Four of the pyridine molecules are located (in a similar fashion to those in 8·Py) so as to form H-bonding interactions with the upper rim calixarene carboxylic acid groups (Figure 4). There are four N···HO interactions and four CH···O interactions with respective distance ranges of 1.773 – 1.875 Å and 2.305 – 2.765 Å.



10 Fig. 4 Part of the asymmetric unit in 9·Py showing hydrogen bonding interactions (dashed lines) between four pyridines of crystallisation and one molecule of 9. Hydrogen atoms (except those involved in H-bonding) are omitted for clarity.

Examination of the extended structure shows molecules of 9 to form a bi-layer array (with an inter-layer spacing of ~ 22 Å) via interdigitation of the O-butyl chains at the lower rim (Figure 5). Bi-layer 15 formation is a common phenomenon with either tetra-O-alkylcalix[4]arenes (and other related calix[4]arenes),²⁰ and the present example is reminiscent of those in previous reports. The remaining pyridine molecules are disordered over several positions, and in addition to those shown in Figure 4, they occupy the space between the bi-layers while forming numerous π-stacking and C···H interactions with aromatic systems of neighbouring molecules of pyridine or 9. As is the case in 8·Py, 20 9 in 9·Py shows both similar conformational distortion in the solid state and subsequent omission of Py from the calixarene cavity. This again precludes pCO₂[4] dimerisation, resulting in a markedly different self-assembly motif relative to the previously reported Py solvates of pCO₂[4]s. 4h,4j

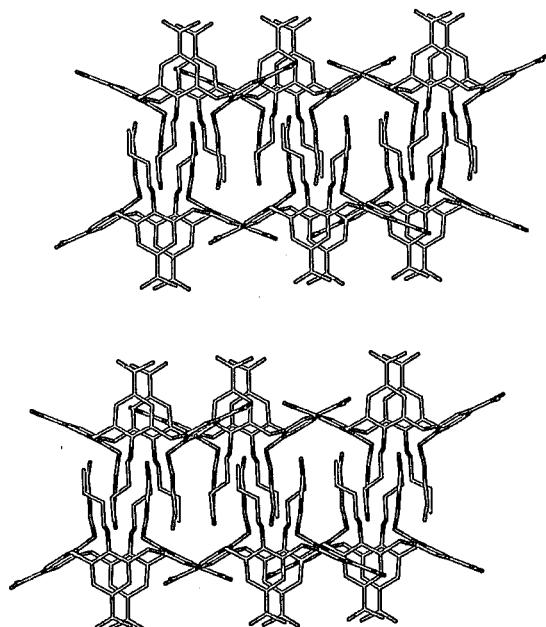


Fig. 5 Part of the extended structure in 9-Py showing the interdigititation of O-butyl chains and the bi-layer array formed. Hydrogen atoms and pyridines of crystallisation are omitted for clarity.

Conclusions

5 In summary, we have shown that tetra-O-alkylated p-carboxylatocalix[4]arenes assemble in markedly different ways when crystallised from pyridine. In particular, these assemblies differ greatly from the previous reported pyridine solvates in that Py is omitted from the molecular clefts of both calixarenes in the solid state. A direct consequence of this substitution is that these molecules do not form the dimers that are typically observed with Py inclusion in pCO₂[4]s which are substituted at the lower 10 rim to lesser extents.^{4h,4j} Future work will focus on preparing and structurally characterising the alkali metal salts of various pCO₂[n]s where n = 4 – 8 to investigate cation influence over self-assembly. Variation in lower rim alkyl chain length will play an important part in their resulting assembly modes, especially in the presence of co-crystallising species such as pyridine.

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Notes and references

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† Electronic Supplementary Information (ESI) available: Crystallographic Information Files and additional unit cells for 8-Py and 9-Py to confirm bulk material composition. See

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‡ Crystallographic General: Data for 6, 7 and 9-Py was collected on a Bruker Apex II diffractometer operating with MoK α radiation ($\lambda = 0.71073$ Å). Data for 8-Py was collected on a Bruker Apex II diffractometer operating with synchrotron radiation ($\lambda = 0.77490$ Å). Crystal data for p-formyl tetra-O-propoxycalix[4]arene, 6: C₄₄H₄₈O₈, M = 704.82, Colourless Block, 30 1.00 \times 0.30 \times 0.20 mm³, monoclinic, space group P21/n (No. 14), a = 12.6194(8), b = 17.1198(11), c = 17.4385(10) Å, $\beta = 98.950(2)$ °, V = 3721.6(4) Å³, Z = 4, T = 100(2)K, 2 θ max = 41.7°, 17274

reflections collected, 3907 unique (Rint = 0.0365). Final GooF = 1.047, R1 = 0.0641, wR2 = 0.1609, R indices based on 2813 reflections with $I > 2\sigma(I)$ (refinement on F2). The crystals were weakly diffracting despite long exposure.

Crystal data for p-formyl tetra-O-butoxycalix[4]arene, 7: C48H56O8, M = 760.93, Colourless Block, 5 0.40 \square 0.30 \square 0.10 mm³, monoclinic, space group P21/n (No. 14), a = 14.2378(16), b = 16.961(2), c = 17.5080(18) Å, β = 98.274(4)°, V = 4184.0(8) Å³, Z = 4, T = 100(2)K, 2 \square max = 41.5°, 20848 reflections collected, 4279 unique (Rint = 0.0571). Final GooF = 1.059, R1 = 0.0564, wR2 = 0.1529, R indices based on 3442 reflections with $I > 2\sigma(I)$ (refinement on F2). A number of restraints were applied due to disorder in one of the formyl groups. The crystals were weakly diffracting despite long 10 exposure.

Crystal data for tetrapropoxy-p-carboxylatocalix[4]arene-pyridine, 8·Py: C133H141N9O24, M = 2249.55, Colourless Needle, 0.24 \square 0.13 \square 0.10 mm³, triclinic, space group P-1 (No. 2), a = 12.2237(6), b = 22.4428(11), c = 24.2799(12) Å, α = 64.188(3), β = 89.399(3), γ = 88.268(3)°, V = 5993.5(5) Å³, Z = 2, T = 100(2)K, 2 \square max = 39.7°, 30229 reflections collected, 10894 unique (Rint = 15 0.0996). Final GooF = 0.925, R1 = 0.0569, wR2 = 0.1119, R indices based on 5866 reflections with $I > 2\sigma(I)$ (refinement on F2). The crystals were weakly diffracting despite long exposure. A number of restraints were applied due to disorder in one O-propyl chain.

Crystal data for tetra-butoxy-p-carboxylatocalix[4]arene-pyridine, 9·Py: C77H85N4O12, M = 1258.49, Colourless Block, 0.70 \square 0.40 \square 0.40 mm³, triclinic, space group P-1 (No. 2), a = 12.236(2), b = 13.141(3), c = 22.319(5) Å, α = 92.18(3), β = 100.82(3), γ = 99.60(3)°, V = 3466.7(12) Å³, Z = 2, D_c = 1.206 g/cm³, F000 = 1342, Bruker Nonius X8 Apex 2, MoK α radiation, λ = 0.71073 Å, T = 100(2)K, 2 \square max = 42.9°, 34541 reflections collected, 7628 unique (Rint = 0.0456). Final GooF = 1.019, R1 = 0.0594, wR2 = 0.1490, R indices based on 5602 reflections with $I > 2\sigma(I)$ (refinement on F2). A number of restraints were applied due to disorder in some pyridine molecules.

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